FINAL REPORT ON
FEASIBILITY STUDY FOR SENSING SULPHIDES IN COAL - 1968

PREPARED FOR

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BUREAU OF DISEASE PREVENTION AND ENVIRONMENTAL CONTROL
NATIONAL CENTRE FOR AIR POLLUTION CONTROL

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Section 1

INTRODUCTION

1. This final report summarizes the work done for the feasibility study, details the laboratory experimentation, circuits and techniques used, gives results and measurements made, and assesses the feasibility of the approaches covered for use as sulphur-in-coal monitors.

2. The progress of work has been reported at three interim stages and support reference should be made to:-

   Progress Report # 1, dated November 1st, 1967
   Progress Report # 2, dated December 1st, 1967
   Letter Progress Report, dated January 12th, 1968

3. The opening section traces in brief the course of the study. This is followed by sections detailing the work of the main approaches into which the study hardened, and the report terminates with resume considerations, assessments, and suggested follow-up work.

Section 2

BRIEF SURVEY OF STUDY

1. In the December of 1966 two coal samples classified as coal without sulphide and with sulphide respectively were tested on an experimental prototype sulphide ore monitor under development for use in the ore mining industry. The principle employed in the monitor is the absorption of power (eddy-current wise) by the conductive sulphide at radio frequencies; and its measurement gives a quantitative indication of the sulphide present. (Progress Report #1 covers the basic principles in greater detail.)

2. At the normal operating frequency of 500 KHz the samples gave some differential readings of a very low order. While this was interpreted as signs of sulphide indications, we stated that other causes may apply. The Contract No. PH-67-270 was raised to perform this feasibility study for a sensor of sulphides in coal, with scope to adapt experimental techniques, increase sensitivities, construct laboratory prototype instrumentation, evaluate samples and provide an evaluation report of the work done and an assessment of feasibility.

3. Work commenced in mid-September 1967, after obtaining initial coal samples. It became apparent that the sulphur content of interest was not the 5% to 36% order initially checked in December, 1966 but was over the 0.5% to 5% band. Circuit changes were made, signal-to-noise ratios improved but the signals obtained were still very weak, the major part being due more to extraneous capacitivity-coupled power absorption rather than eddy-current power transfer.

4. Frequencies were increased to induce an increased loss into the very small particles of sulphide, and while some frequency increase had been originally envisaged it was found that even at 50 MHz with shielded coils there was

still no worthwhile indication of power absorption into 5% sulphur coal. It should be mentioned that 40% sulphur samples throughout the above phases gave worthwhile signals, but of course true interest was now confined to the 5% high sample range.

5. Frequencies were increased and entered the microwave region, coils became smaller, and the coal samples had to be pulverized. Finally with an abbreviated "coil" and "grid dip" circuit between 800 MHz and 940 MHz (the limit for this hardware) sharply increasing signals were obtained, which correlated with the sulphur content sequence of the samples.

6. For work at higher frequencies it was obvious that the coil configuration would have to be replaced with waveguide and cavity constructions. Equipment was assembled for this purpose and the frequency range 500 to 1100 MHz was covered to check agreement with the "grid dip" circuit method. Qualitative agreement was evident and the coaxial cavity method showed acceptable differential signals over near zero to 5% sulphur samples even below 800 MHz. It should be kept in mind that attention was confined to effects ascribable to "eddy current" absorption of power in lossy, impure bulk material rather than diffusing much effort in pure microwave absorption spectroscopy observations as such.

7. Before this higher frequency work had started, other methods were suggested centering around the conversion of some of the surface sulphur into SO_2 and quantitatively detecting the gas with a SO_2 spectrometer monitor. Accordingly, high intensity Xenon flash and quartz-iodine lamps were used, but results were negative, except when the surface of the coal was visibly smouldering. This led to the construction of a flash heater or volatilizer into which pulverized samples (at low flow rates of the order of one gram a minute) could be burnt under controlled conditions and the resultant SO_2 detected and measured by the spectrometer to give a proportional indication of the sulphur content of the sample. Results with this method showed very accep-

table linearity over the range of interest. In ultimate use the arrangement is envisaged as giving a continuous indication, using a continuously-drawn small sample.

8. Thus two main methods evolved during this feasibility study - microwave and SO_2 spectrometry, and details are given in the follow-up sections. It is encouraging to say that work ceased only as a result of reaching the agreed cost and time scheduling limits of the study. Definitely worthwhile follow-up work is indicated.

Section 3

LISTING OF SAMPLES USED

The following is a tabulation of the coal samples used during the various phases of this feasibility study. These were obtained from Dr. Gluskoter:

Barringer Sample No.	Type	Total Sulphur Content As Estimated	Total Sulphur Content When Analyzed	Analyzed Pyritic Sulphur
1	Herrin #6 Coal	1.25%	1.81%	0.88%
2	Danville #7 Coal	3 to 4%	2.89%	0.92%
3	Perry County Coal and Pyrite	lower than #4	18.36%	15.49%
4	"	High content	56.57%	44.84%
5	50/50 mix of #2 & 3 (by weight)	10.62%	10.38%	8.09%
6	13/1 mix of #2 & #3	4.0%	4.78%	3.22%
7	6/1 mix of #2 & #3	5.0%	6.04%	4.41%
8	Herrin #6 Coal	0.8%	0.98%	0.31%

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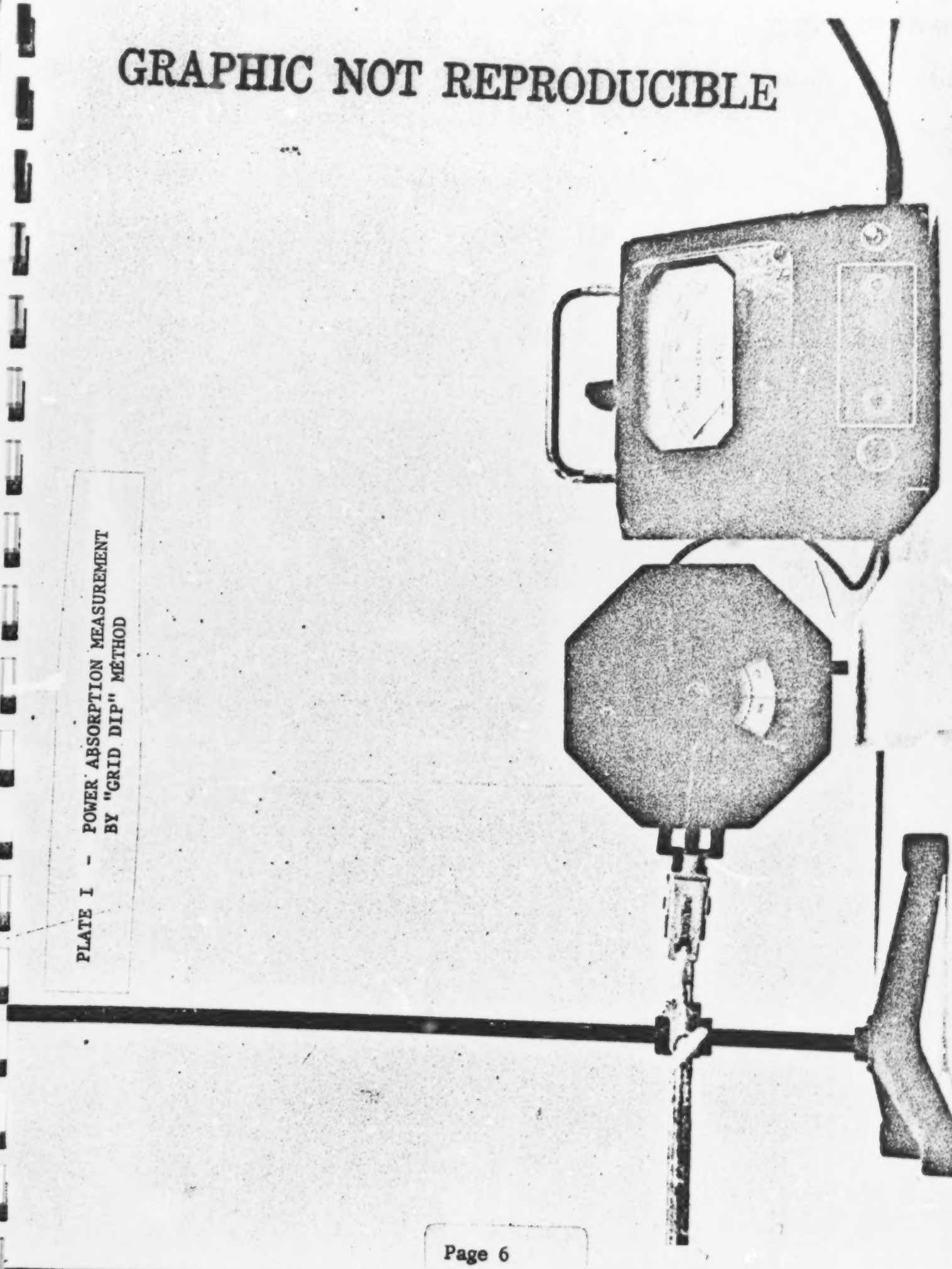

PLATE I - POWER ABSORPTION MEASUREMENT BY "GRID DIP" METHOD

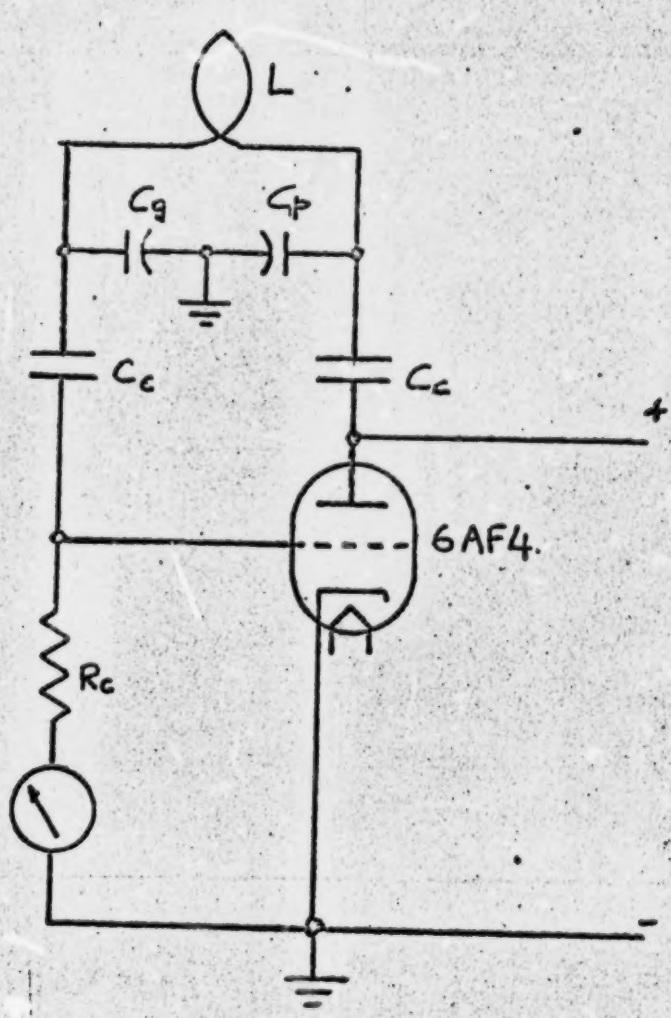

FIG 1 – OSCILLATOR BASIC CIRCUIT
(UP TO 940 MHz)

Section 4

WORK UP TO 940 MHZ

1. For power absorption experimentation up to 940 MHz, a "grid dip" type of circuit configuration was used. The basic configuration, shown in Figure 1 (omitting filtering and decoupling components, power supplies, etc.), is a Colpitts type oscillator, the inductance 'L' being the exploratory single turn U-shaped 'coil' of 1/4" wide strip, 1/2" high x 1/8" gap.

2. Circuit oscillation involves grid current flow for part of each cycle. This current is uni-directional (through the grid-cathode 'diode') and its average effect registers on the meter shown and through the resistor 'R_C' controls the self-bias of the grid. When lossy media couple with the coil, power is dissipated, the coil 'Q' falls and the bias condition alters, registering as a proportional dip in the average grid current indicated on the meter.

3. At these high frequencies power absorption effects are readily influenced by conditions adjacent to the coil and changes in readings are easily occasioned by small changes in the position of sample holder, slight differences in penetration depth of the coil in to the sample, extraneous capacitive coupling effects to adjacent objects etc. For uniform assessment the sample grains must be small compared with the coil dimensions and thorough mixing is required to ensure homogeneity for repeatable results.

4. The experimental procedure (see Plate I) involved setting up the circuit head in a rigid clamp with the coil loop projecting downwards. Pulverized samples of coal were uniformly sieved (.015" mesh openings) and filled into sample holders. These sample holders were made of low-loss urethane foam containing accurate cavities of 1" diameter x 1" deep, and the samples were filled flush to the top surface. The samples were raised against the coil,

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FIG. 2 - RELATIVE POWER ABSORBED PER UNIT VOLUME AS A FUNCTION OF FREQUENCY

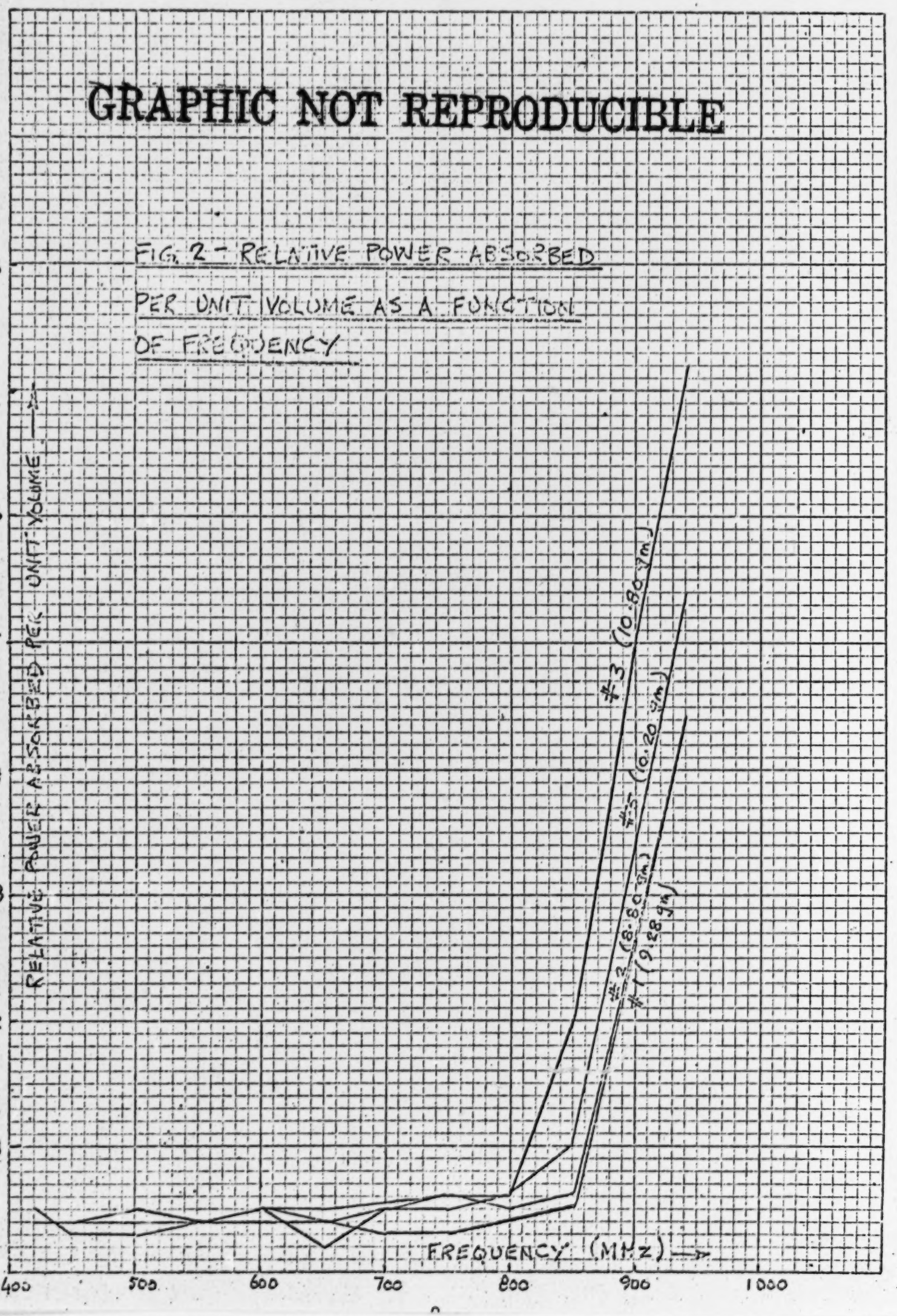

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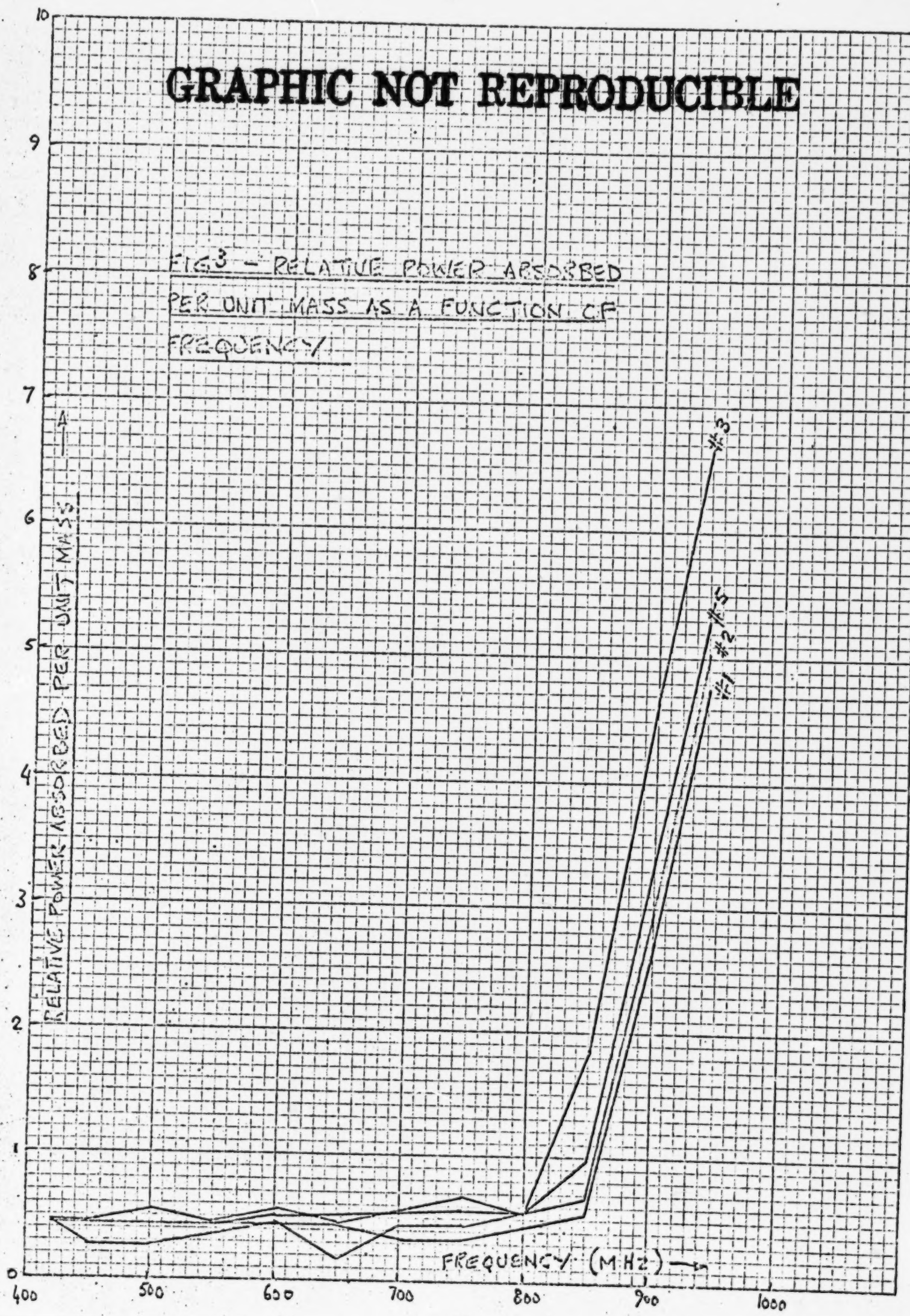
FIG 3 - RELATIVE POWER ABSORBED PER UNIT MASS AS A FUNCTION OF FREQUENCY



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so that the coil loop penetrated into the sample, and the holder was gently vibrated into position to ensure even packing of the sample around the loop and uniform positioning. After reading the signal, the sample was withdrawn, "zero" signal checked, and frequency stepped, and the process repeated. After the full frequency range had been explored the sample was weighed.

5. Sample Nos. 1 through to 5 were in use for these tests, and only the estimated sulphur contents were available at the time of experimentation. Frequencies from 420 MHz up to the instrumental limit of 940 MHz were used and the results are shown plotted in Figure 2 (on a per unit volume basis) and Figure 3 (on a per unit mass basis). Sample No. 4 is not classifiable as a coal, being specially selected high density pyrite inclusions. To avoid confusion its readings are omitted here, but are detailed and discussed in Report #2.

6. Below 800 MHz the power absorption is relatively small with haphazard minor fluctuations. Commencing above 800 MHz the power absorption on all samples shows a rapid increase and the quantitative order of increasing power absorption of the samples lies in the sequence 1, 2, 5, 3 which agrees with the sequence of increasing sulphur content.

7. Figures 4 and 5 illustrate the degree of correlation at 940 MHz between the power absorption signals and the analyzed sulphur content on a per unit mass basis (Figure 4) and absence per unit volume basis (Figure 5) against both pyritic and total sulphur.

8. One interpretation shows linear correlation appearing on a per unit mass basis against total sulphur, with a sensitivity indicated by an approximate relative power change from 90% to 100% for a commensurate sulphur content change from zero to 5%. Another interpretation points to linear correlation showing up on a per unit volume basis against pyritic sulphur.

9. The results were made with samples having a long term exposure to normal room humidity conditions. Comparative checking between such samples and

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FIG 4- POWER ABSORPTION PATTERNS (PER UNIT MASS BASIS) AT 94.0 MHz FOR FOUR COAL SAMPLES.

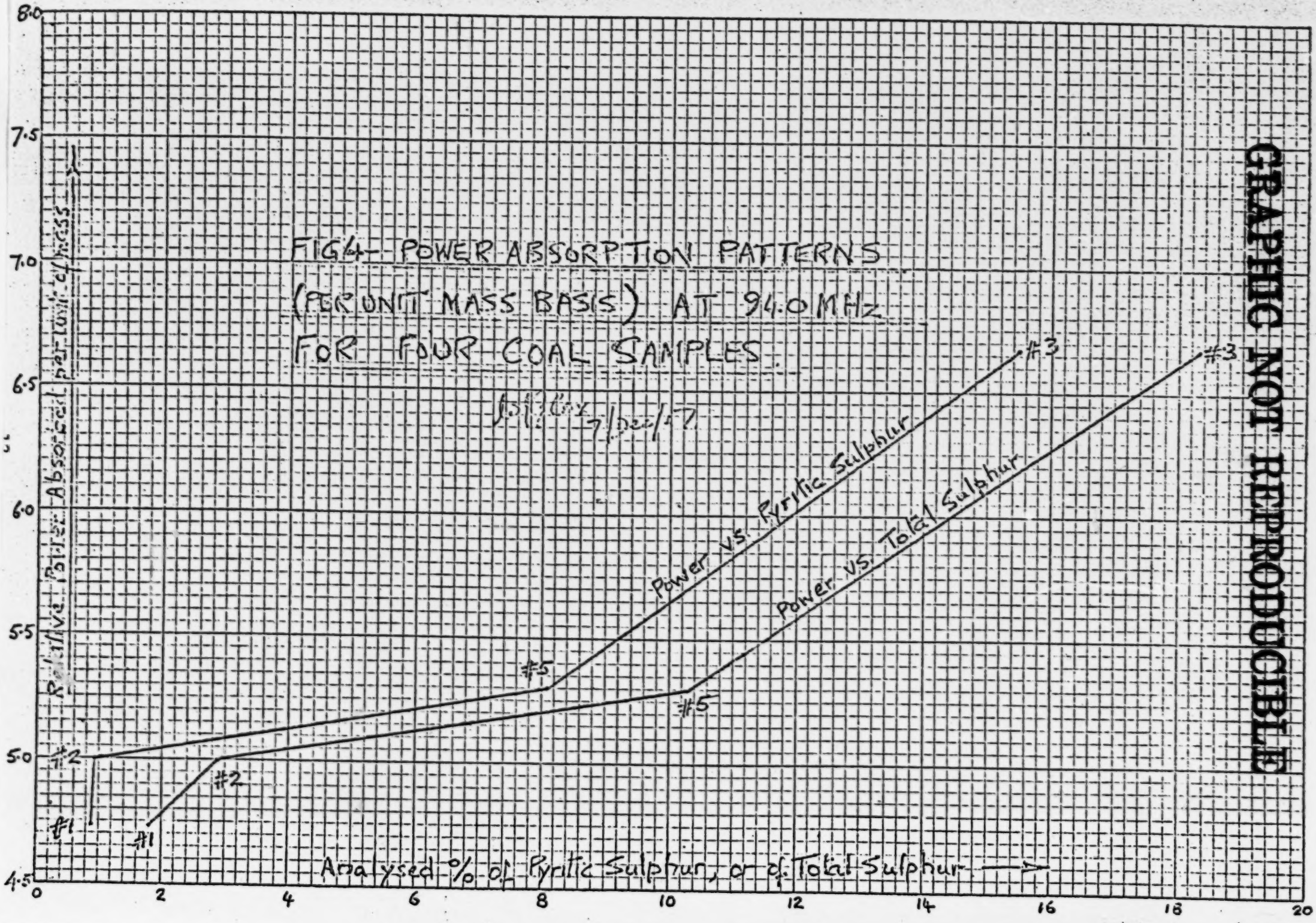

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FIG 5 - POWER ABSORPTION PATTERNS
(PER UNIT VOLUME BASIS)
FOR FOUR COAL SAMPLES AT 94.0 MHz

Relative Power Absorbed per unit of volume

Attenuated % of Incident Power — Total Sulphur

#1 #2 #3 #4 #5 #6

- 13 -

their power absorption at 900 MHz after prolonged drying out showed a response reduction of approximately 3%.

10. The increasing response trend at 940 MHz suggested further investigations at higher frequencies. This involved a wave-guide cavity approach which is described in the next section.

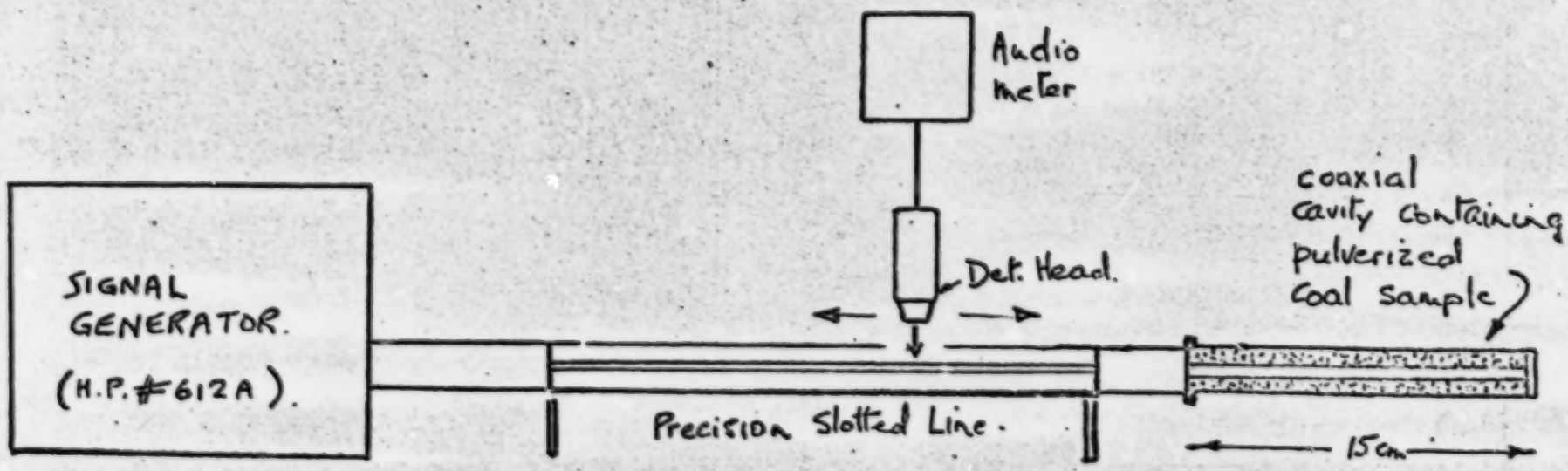


FIG. 6. – EXPERIMENTAL SET-UP FOR MEASUREMENTS UP TO 1200 MHz.

Section 5

WORK WITH COAXIAL CAVITIES, ABOVE 940 MHZ

1. Figure 6 shows the set-up of the microwave gear for measurements higher than 940 MHz. It was considered necessary to repeat coverage from 500 MHz upwards to check the degree of agreement with the previous results obtained by the method detailed in Section 4.

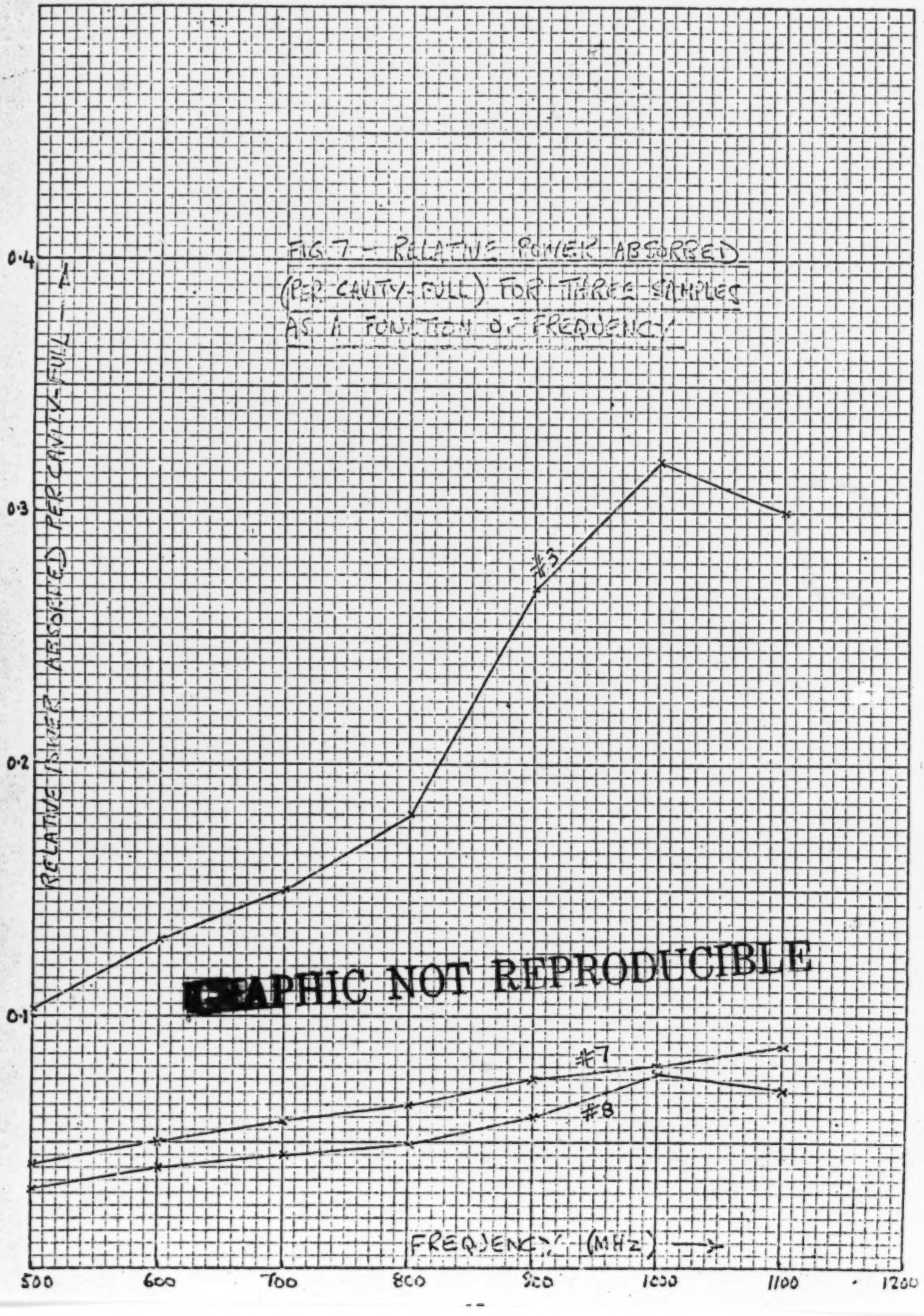
2. The method is a standard procedure for the measurement of powerloss at frequencies of the order of 10^9 Hz in lossy dielectric material (i.e. material exhibiting a complex permittivity), and is described typically in the reference*. Briefly, microwave power is launched into a line terminating in a perfect short circuit, return power being fully abosrbed by the signal generator which has its output impedance matched to the line characteristic impedance. The line comprises a precision slotted section with a micrometer-positioned detector probe used for the precise location and amplitude determination of standing-wave nulls along the section. This precision slotted section is connected to an end-shorted coaxial cavity section into which the pulverized sample can be introduced. The detector probe demodulated signal is connected to an audio meter, a low frequency 400 Hz modulating signal being provided by the microwave signal generator.

3. When the cavity section is empty, the line can be considered loss-less and checks out accordingly, showing standing wave node nulls of near-perfect zero amplitude. Introduction of the lossy material affords a second null measurement (now an "imperfect" null due to amplitude attenuation and phase change of waveform) and from these measurements the power abosrbed by the material can be calculated.

4. Similar experimental precautions to those mentioned in Section 4 had to be observed. In particular it was found that the mixing and stirring up of

*"Dielectric Materials and Applications" - A. Von Hippel, Publishers-Technology Press of MIT, and J. Wiley & Sons Inc. - Companion Book-"Dielectrics & Waves" - A. Von Hippel

FIG 7 – RELATIVE POWER ABSORBED (PER CAVITY-FULL) FOR THREE SAMPLES AS A FUNCTION OF FREQUENCY



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7 X 10 INCHES
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FIG 8a- POWER ABSORPTION PATTERNS AT VARIOUS FREQUENCIES FOR THREE SAMPLES OF A PYRITIC SULPHUR CONTENT BASIS, USING COAXIAL CAVITY METHOD

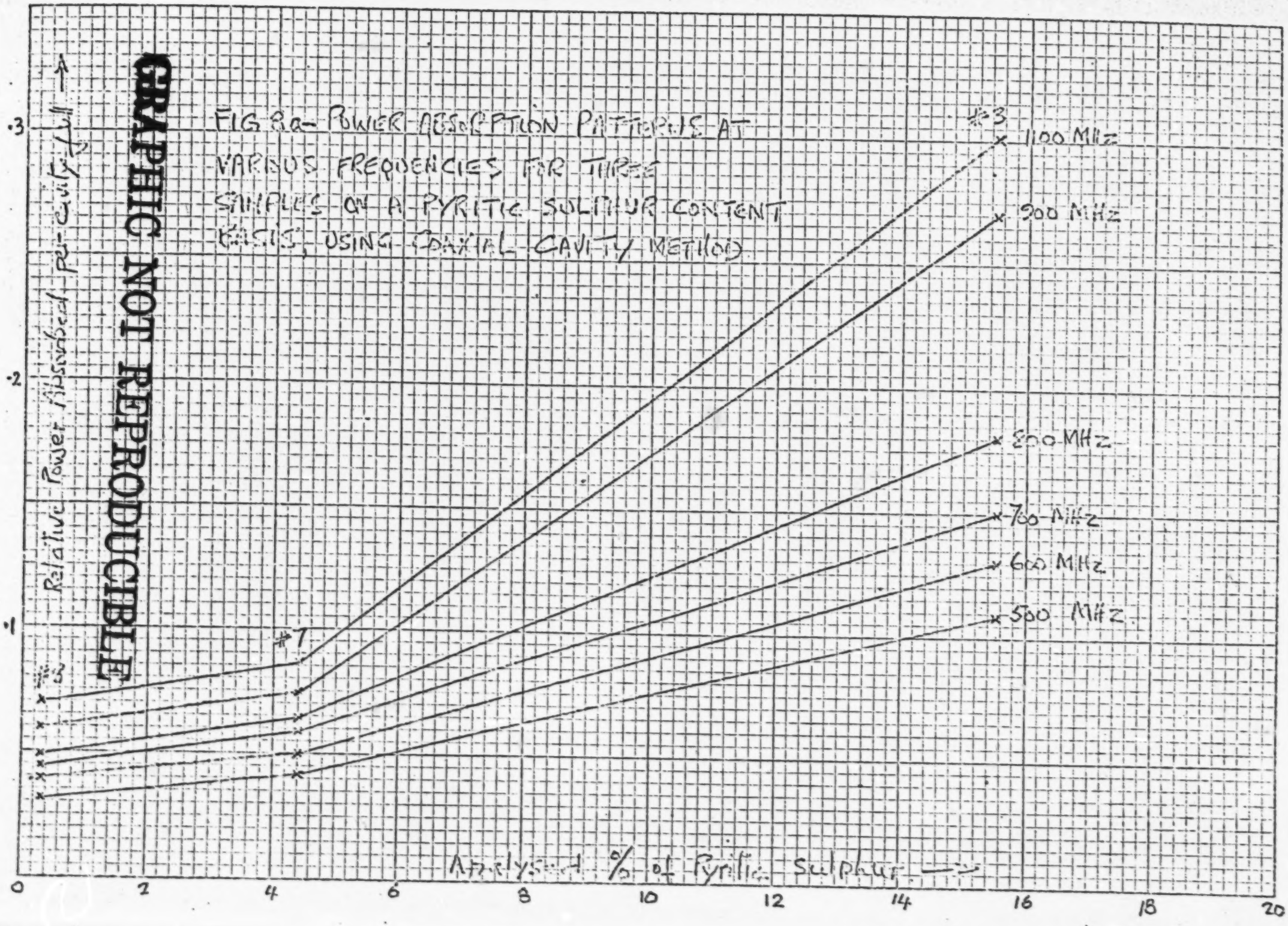

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FIG 8b - LAYER ARRANGEMENT OF
VARIOUS FREQUENCIES FOR THREE SAMPLES
ON A TOTAL SUBLIME CHEMENT BASIS,
USING GIVEN SUBLIMATION METHOD

samples to improve homogeneity had to be very thoroughly undertaken for repeatable results. The measurements are strictly on a "per cavity full of material" basis and not per unit mass.

5. Figure 7 shows the results obtained using samples Nos. 8, 7 and 3 which are in a sequence of increasing sulphur content, and agree with the order of increasing power absorption measurements derived. Figures 8a and 8b present the data so that correlation against pyritic and total sulphur respectively can be better appreciated. At 900 MHz the sensitivity is indicated by an approximate relative power change from 75% to 100% for a commensurate sulphur content change from zero to 5%.

Section 6

DISCUSSION AND COMPARISON OF RESULTS USING THE TWO MICROWAVE METHODS

1. A good comparison of the results from the two methods is afforded by Figures 2 or 3 and 7. The coil method up to 800 MHz shows no differentiation between the high sulphur #3 sample and the lower sulphur # 1, 2 and 5 samples, whereas the coaxial cavity method clearly differentiates between #3 and the lower sulphur # 7 and 8, and also correctly differentiates between #7 and #8 over this 500 to 800 MHz range of frequencies, with steadily increasing signals.

2. Above 800 MHz (to the limit 940 MHz) the coil method shows a sudden sharply increasing power absorption on all the samples with the sequence expected from the sulphur contents. The coaxial cavity method shows a rate increase of signal for #3 above 800 MHz (but not as steep as for the coil method), a smaller rate increase for #8, and virtually no change in rate for #7, which shows a uniform and steady increase of signal over the whole 500 to 1100 MHz band.

3. At 1000 MHz there appears to be an optimum peak signal for #8 and #3 samples. Readings could only be carried up to 1100 MHz with the signal generator in use, and it would be preferable to have response figures well above 1100 MHz to confirm the true validity and extent of such an optimum, particularly as it is not displayed by the #7 sample characteristics. The precautions to be observed in getting repeatable results are discussed elsewhere, and the experimental exigencies may well disguise shallow peaks.

4. It is suggested that the differences in results over the common frequency regions of Figures 2 or 3 and Figure 7 to a certain extent reflect the differences in the degree of efficient use of the microwave energy, control

of experimental parameters which apply to the two methods, and the different spatial field geometries. In the coaxial cavity method, the energy was constrained witin the fixed linear geometry of transmission lines and cavities, and measurements accounted for input, return and absorbed power. In the "grid dip" circuit method, energy was radially broadcast from the "coil" and the sample was located centrally close around the coil to absorb a proportion, lower the coil "Q", and accordingly register a dip in grid current.

5. The peaking of signals at 1000 MHz in Figure 7 could very well be associated with the fact that the sample cavity is a sympathetic half-wave length at that frequency. On the other hand the very different geometry of the coil method shows in Figure 2 a sharp absorption increase pointing to resonance effects also in the region of 1000 MHz.

6. The signal sensitivity to change in sample positioning and indeed to any dimensional changes of the experimental set-up together with the short wavelengths in use suggest that a "per unit volume" assessment of power absorption effects is more valid than a "unit mass" basis. The difference is small (as there is not much change in coal density over a zero to 5% sulphur change), but the Figure 5 representation (rather than Figure 4) should apply. Here the power absorbed correlates better with the conductive pyritic sulphur rather than total sulphur, supporting the surmise that power absorption is still accountable by an eddy current mechanism.

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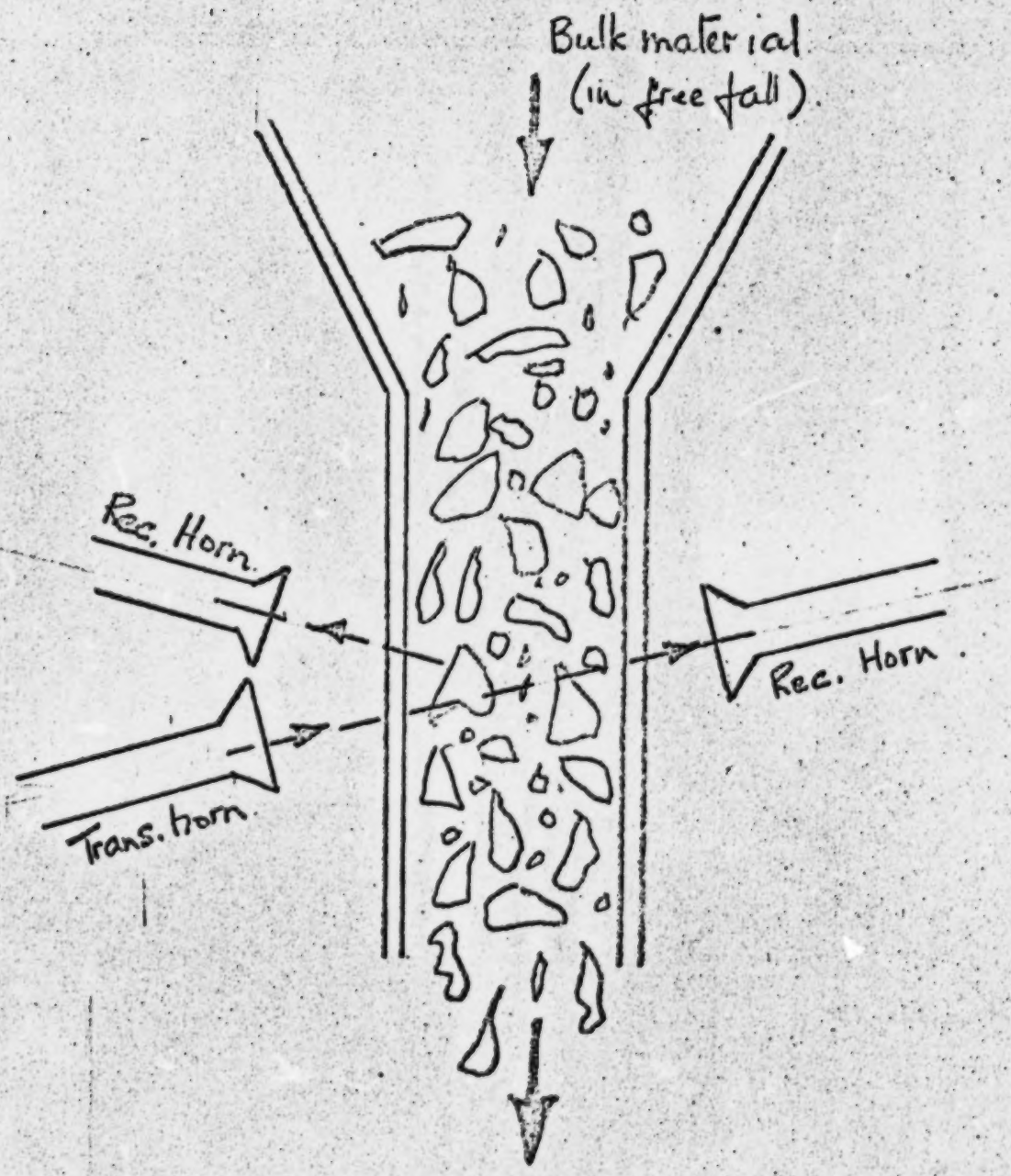

FIG. 9 - SUGGESTED MICROWAVE MONITORING EXPERIMENTATION FOR BULK MATERIAL.

Section 7

RESUME ON MICROWAVE METHODS

1. There appears to be reasonable experimental grounds for stating that the variation of pyritic sulphur in coal shows up as a sympathetic variation in microwave power absorbed, over the higher hundreds of MHz of frequency used.

2. Dependant upon the care taken in the instrumental set-up and control of parameters, preparation of sample etc., an adequate signal differential appears feasible for a pyritic variation up to 5%. Higher pyritic contents are registered also at lower frequencies and with less stringent control of experimental parameters.

3. Resonances in power absorption are to be expected. In particular, both methods disclose a likely resonance at 1000 MHz which needs further critical examination.

4. Follow up investigation is indicated at higher frequencies on different sieved sized particles, and also on methods of using microwave on bulk material rather than highly processed, pulverized sample streams. For example, bulk material falling in a constrained space (Figure 9) between the horns of transmitters and receivers may in practice provide sufficiently accurate information on a statistical basis. Input, transmitted and reflected power could be integrated over a sample time together with material flow to assess average power absorption per unit of material over the sample time. It is true that instantaneous values of reflected and transmitted power will vary with the instantaneous orientation and size of the pieces of material in the bulk flow, but spatial and temporal averaging effects will apply.

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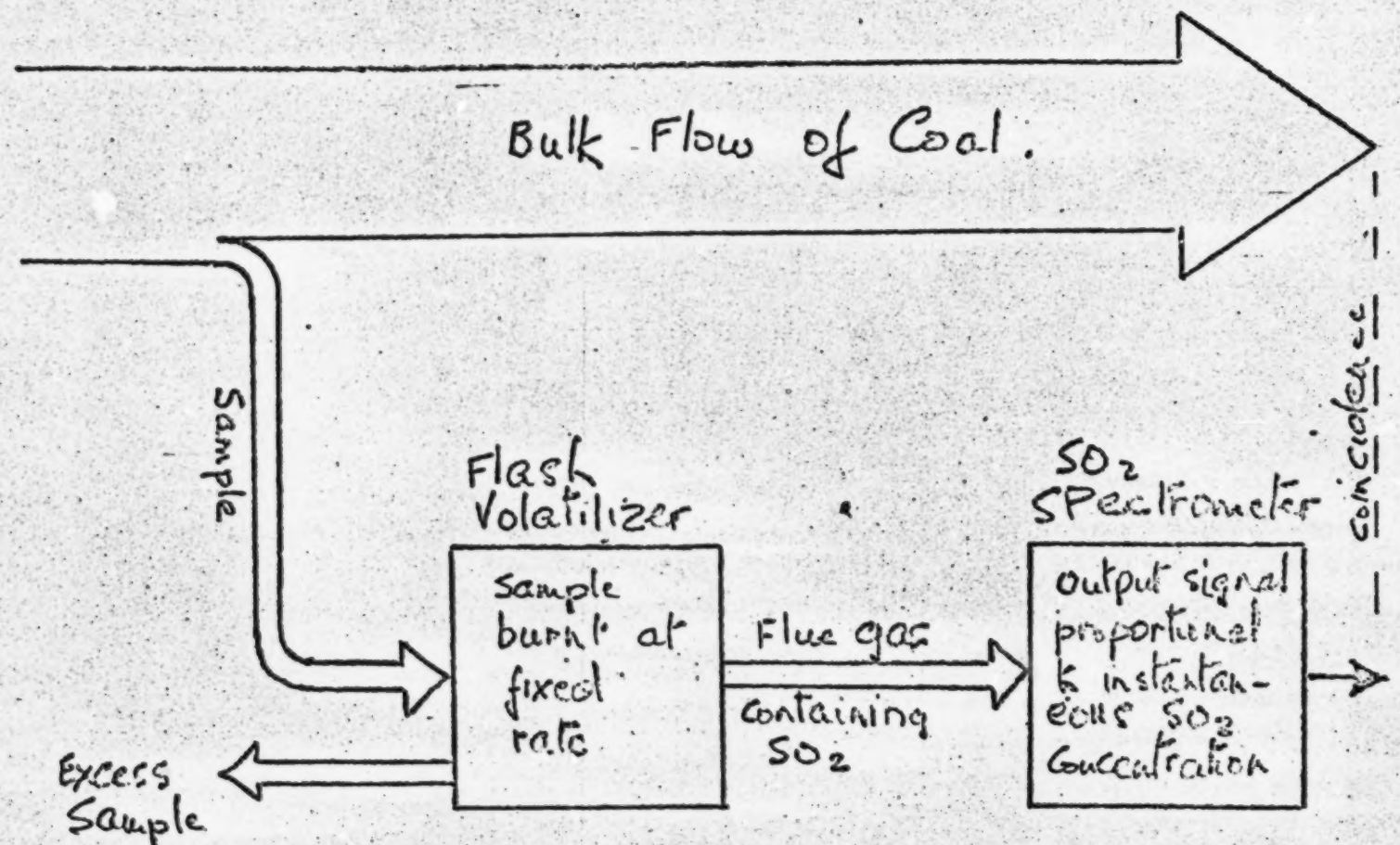

FIG. 10 – BLOCK DIAGRAM OF SO_2 SPECTROMETER METHOD USING FLASH VOLATILIZATION

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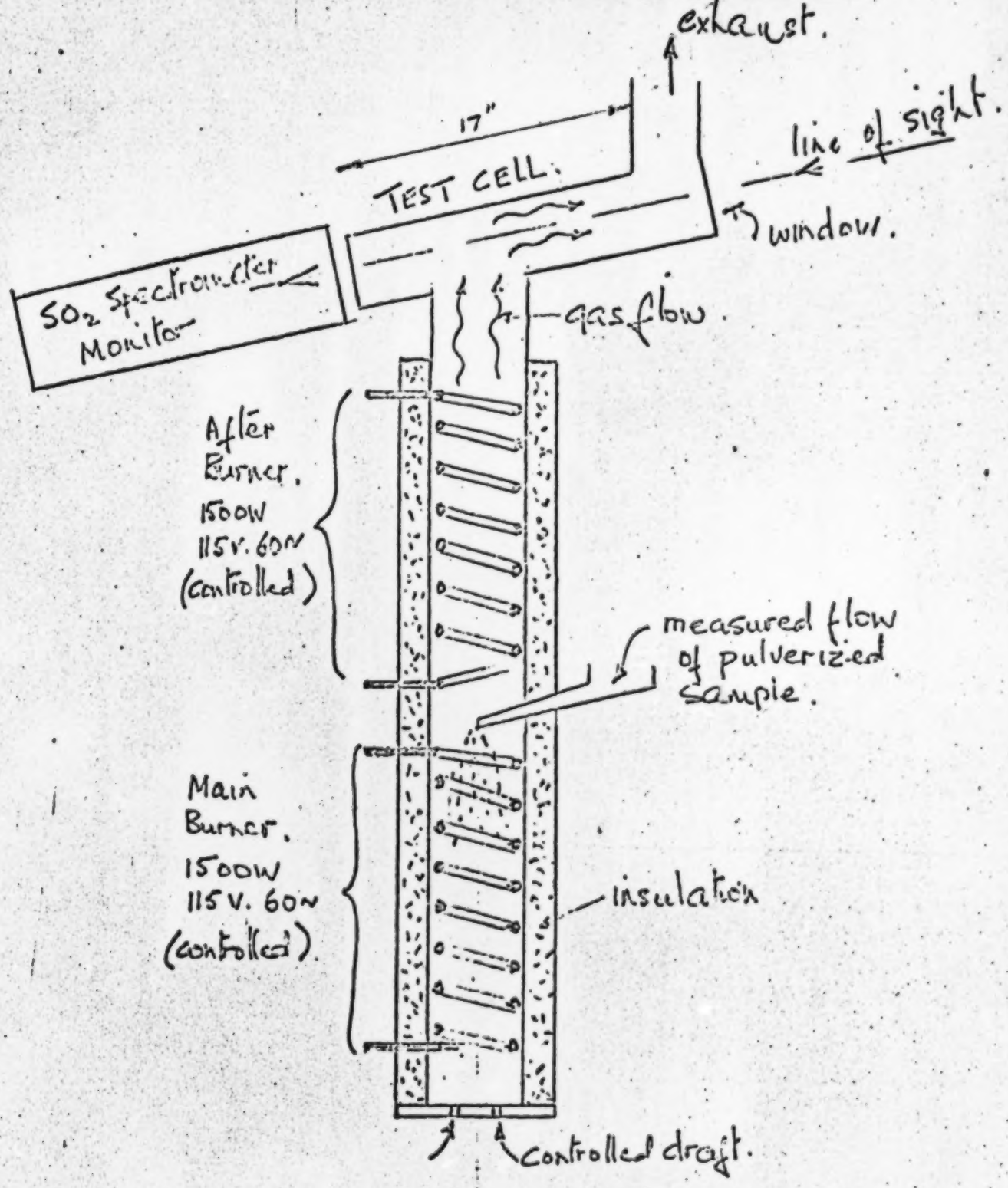
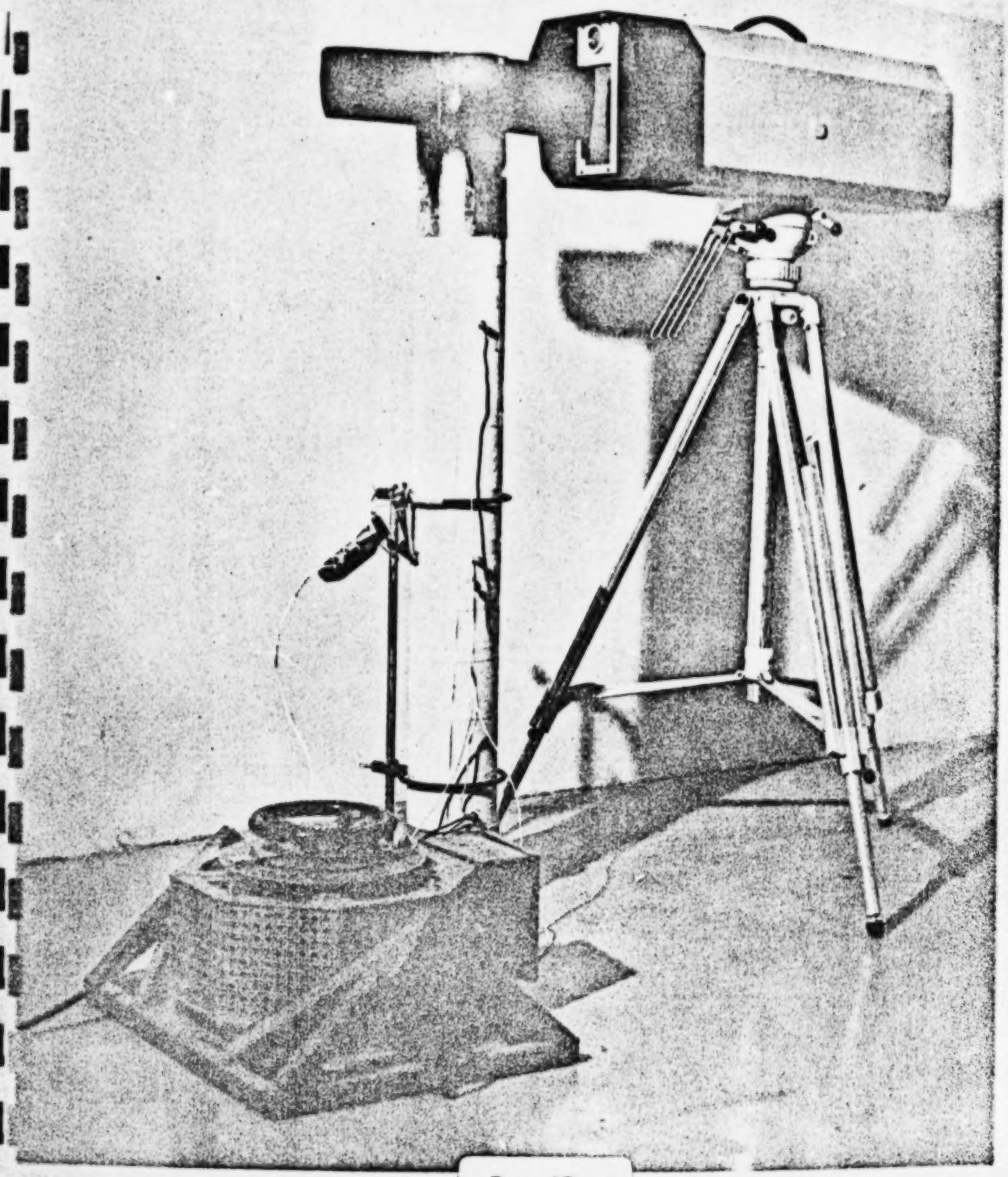


FIG 1: - SKETCH OF MINIATURE VOLATILIZER

PLATE II - EXPERIMENTAL FLASH VOLATILIZER AND SO_2 MEASURING SPECTROMETER



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Section 8

FLASH VOLATILIZATION AND CONTINUOUS SENSING OF SO_2 USING SPECTROMETER

1. During the early part of the feasibility study when the lower frequency results were negative, the use of the Barringer SO_2 Spectrometer presented an alternative as a means of assessing the sulphur in coal in a continuous fashion. The method envisaged is illustrated in the block diagram of Figure 10. A continuous sample is trimmed to a fixed rate, burnt at this rate and the flue gas viewed with the SO_2 spectrometer. The spectrometer signal amplitude is the instantaneous measure of the concentration of SO_2 which in turn is a measureof the sulphur concentration in the coal sample, assuming factors which affect combustion, draft etc. are maintained constant. If required, the time taken in processing the sample could be arranged to match a transport lag in the bulk flow of the coal so that the concentration signal could be available coincidentally with the appropriate section of the bulk material at a desired station.

2. To check the feasibility of this approach, an experimental flash volatilizing unit was constructed as illustrated in Figure 11. The unit consists of a hollow vertical tube of high temperature thermal insulation material, and contains two helix-formed heating elements, each of 1500 watts. The bottom end of the tube is closed off with a perforated plate having a shutter positioned to control the natural draft. The upper end of the tube is connected to a slightly sloping chimney, open ended as shown so that the flue gas would flow along the sampling line of sight ofthe SO_2 Spectrometer. The experimental set-up is shown in Plate II.

3. The pulverized coal sample is introduced through a chute which is continuously vibrated to maintain a reasonably even flow. The coal dust enters the hollow vaporizer between the two elements. The low element combusts the coal, and

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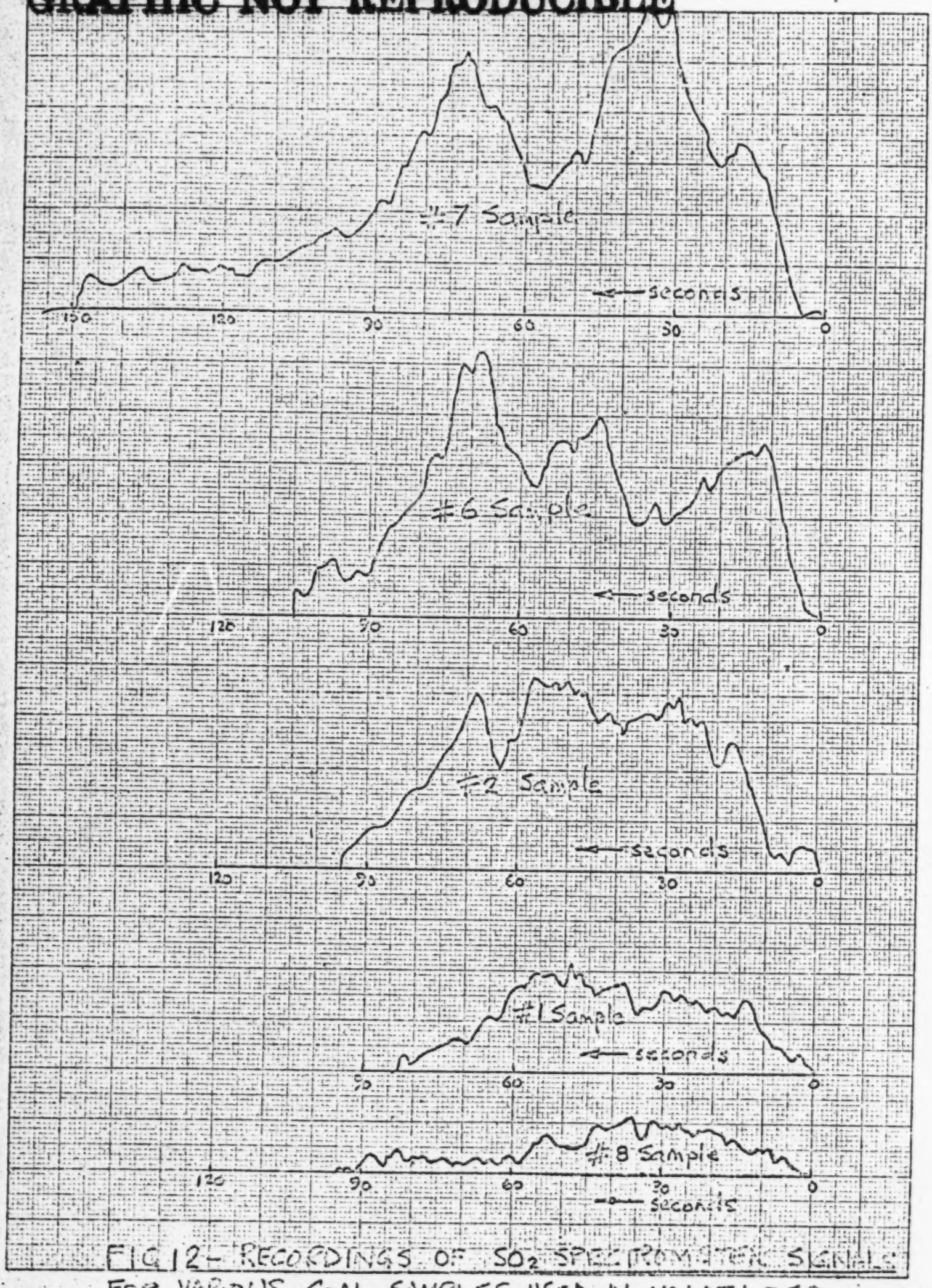

FIG 12- RECORDINGS OF SO_2 SPECTROMETER SIGNALS FOR VARIOUS COAL SAMPLES USED IN VOLATILIZER.

the upper element serves to complete combustion of the flue constituents. Both heating elements are variac-controlled so that an adequate but safe temperature is available for combustion, and the draft is regulated so that sufficient air is present for complete burning without too much excess to weaken the SO_2 concentration in the flue.

4. The experimental unit was arranged for burning approximately 1 gram of coal per minute, the flue draft velocity being 0.5 ft./sec., and the useful flue test sample length being 17 inches. Under these conditions the second range (500 mv) of the spectrometer could be used to cover signal excursions expected from coal containing up to approximately 5% sulphur.

5. Continuous operation was not possible for this feasibility testing as only limited samples were available. The procedure adopted entailed pulverizing and mixing the sample, stabilizing the temperature and draft of the flash volatilizer, zeroing the output recorder and introducing 1 gram of the sample into the vibrating chute. Recording was continued until the signal fell back to near zero (indicating completion of combustion). The process was repeated with other samples. Some typical recording traces are shown in Figure 12. It will be noticed that while the coal dust runs for 60 to 80 seconds, SO_2 evolution continues beyond this time. This is due to collections of dust on the interior parts of the heater (particularly the bottom plate) which continues to burn for a short while after the main stream of dust has run through.

6. Figure 13 shows the order of proportional agreement between the spectrometer integrated signal and the total sulphur contents of the coals. The vertical bars estimate the extent of experimental error. Of course under continuous steady sample operation, the integration of the signal is not required; its amplitude is a moment-to-moment indication of the percentage sulphur in the coal sample.

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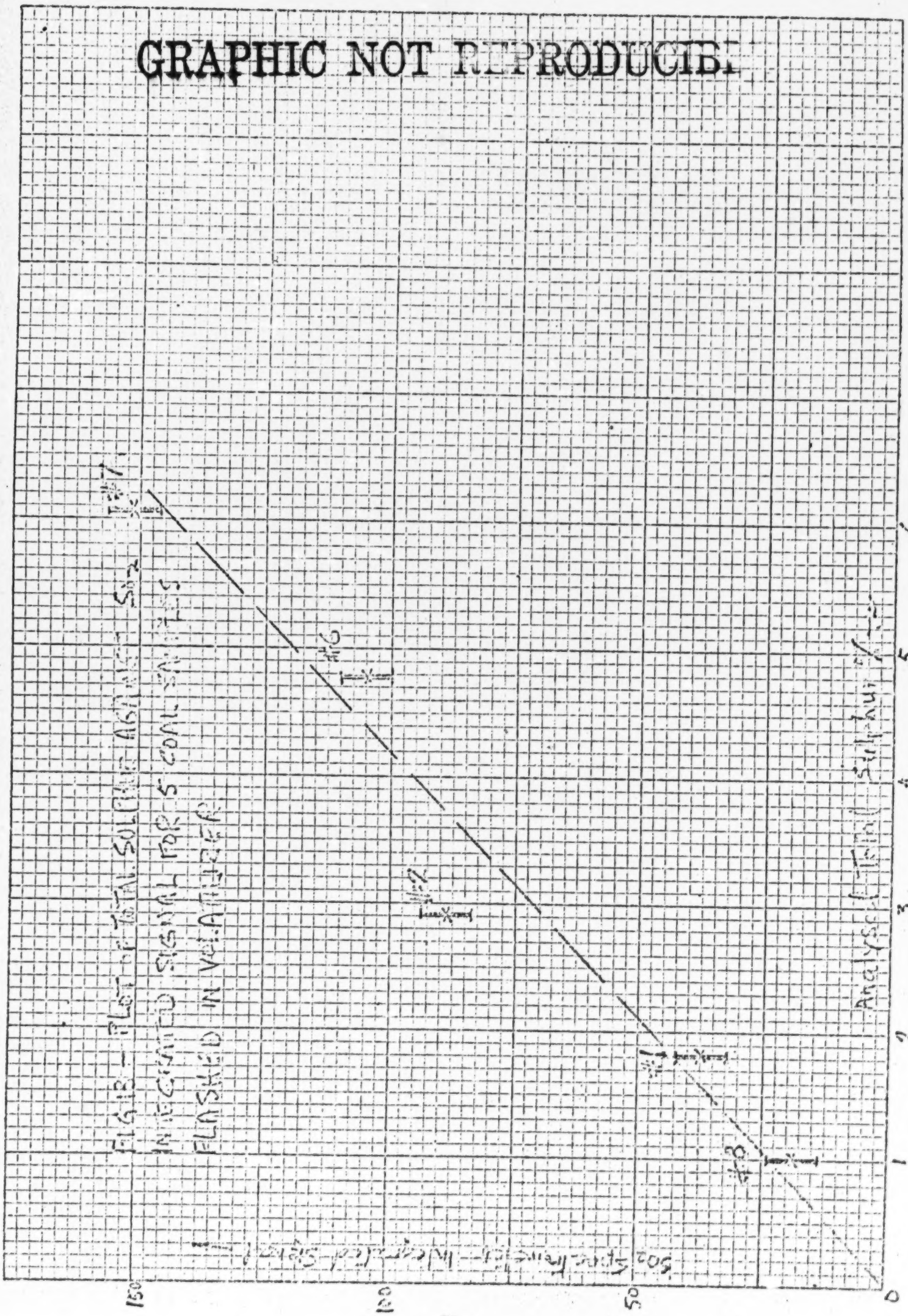
FLASH DISTANCE IN METERS
FLASH DISTANCE IN FEET
Analysis of Illuminating Gas
Sulphuretted Hydrogen
Ammonia
Carbon Bisulphide
Sulphur Dioxide
Hydrocyanic Acid
Naphthalene
Tar
Ammonia
Sulphur
Cyanogen
Carbon Bisulph

Section 9

DISCUSSION ON THE SPECTROMETER METHOD

1. The ease with which the experimental gear went together and functioned to give reasonable results right from the start indicates a certain merit which deserves consideration. Remedial measures to most of the functional faults which showed up during the experiments appear self-evident, and a reasonably clear idea of a final unit can be envisaged.

2. The main requirement is a representable, fractional sample of the bulk flow of coal, and this must be the problem facing existing analytical methods.

3. Our requirement for a few grams per minute of representative dust from a conveyed stream would be met if at a convenient transfer point from one conveyor to another a small fall was permitted to create some dusting, and this dust was continuously vacuumed off, collected and introduced into our monitoring cycle. It is not known whether the pyrite dust would gravitate differently from the coal to give an unrepresentative sample, but if the dust is really collected "on the fly" it is difficult to picture on the face of it a simpler way of getting a small dust sample stream representative of a coarse-lumped main stream across the whole conveyor belt. Variable dampness may be another hazard to uniformity of dust collection, but practical investigation is suggested as very worthwhile.

4. The output signal could be presented in a number of ways to suit data handling or control schemes. The final pulverized coal sample feeder is pictured as a spiral screw rotor turning in a close-fitting tube housing to convey the coal from a small hopper to the dispensing end in the furnace, the housing being water-cooled to prevent coking up in the tube. A constant-speed motor drive would actuate the screw to give a uniform rate of coal feed, the variable sulphur content being determined by the variable signal output of the SO_2 spectrometer. Alternatively a closed loop form of operation could

be adopted using a variable speed drive for the screw, the speed being controlled by the SO_2 spectrometer signal used in a null sensing mode against a comparison standard reference.

Section 10

CONSIDERATIONS AND SUGGESTIONS FOR FUTURE WORK

1. At the microwave frequencies dealt with in the report there are clear indications that changes in pyritic sulphur from zero to 5% in coal can give adequately differentiated power absorption signals. However, the requirements are:-

   (a) Fully representative sampling.
   (b) Prepared, pulverized and thoroughly mixed samples.
   (c) Good control of all instrumentation parameters and sampling factors.

2. The requirements being met, the obvious system pictured from the work of this study would function on a cycle of stages:-

   (a) Standard sized sample abstracted from main sample.
   (b) Sample packed uniformly into cavity or around a small antenna space.
   (c) Measurement made.
   (d) Sample emptied off.
   (e) Repeat cycle from (a).

   There is no doubt that the use of an antenna or coil is to be preferred to a cavity as a practical arrangement, and there appears to be no fundamental reason why such a cyclic procedure should not achieve frequencies of the order of ten per minute to give a good approximation to continuous monitoring. However the main requirements for representative and prepared sampling form an initial necessity.

3. To avoid the sampling phase, the suggestion is made in Section 7, paragraph 4 and figure 9 that bulk material may be amenable to satisfactory statistical monitoring. We know that differential signals exist from the work of this feasibility study. The aspect to be settled by experimentation would be

whether there is sufficient differentiation of accumulated signals over reasonable integration times to allow for all worthwhile changes in particle orientation and mixing of bulk samples. Only practical testing can disclose this, and the benefit, if successfully demonstrated, would be a system working on a full flow of bulk material without interference or sampling. Experimentation could be on the lines suggested by figure 9, with large amounts of full sized "as is" coal specimen, constrained in a fixed large environmental space (large enough to simulate actual conveyed sections) and make power absorption measurements over a variety of parametric changes (mixing, orientation and position of large and small particles, changes in position and numbers of microwave horns etc.).

4. Considering the flash heater and SO_2 spectrometer, here also experimentation has shown the capability of this approach in producing clearly differentiated signals over the sulphur ranges of interest, and it could be engineered into a continuously monitoring system. Here again, a basic requirement is representative sampling, though not to such stringent requirements of quantity, particle size, and mixing as is demanded for microwave work.

5. A possible method has been suggested in outline for suction collecting a representative (continuous) dust sample from bulk conveyed coal which, if proved valid experimentally, would fit into the requirements for both the microwave and spectrometer approaches.

6. Thus in conclusion, the suggestions for future follow-up work in support of this feasibility study may be itemized:-

   (a) Experimentally check the validity of suction collection of dust to give a representative continuous pulverized sample of the bulk material (Section 9.3 and Section 10.5).

   (b) Additional support work at 1000 MHz and above (Section 7.3).

(c) Careful experimentation with a "coil" or antenna below 800 MHz to check if results from coaxial cavity work can be reproduced by this more convenient construction (Section 6.4).

(d) Experimentation with large samples of bulk material to bypass sampling and pulverizing requirement (Section 7.4 and Section 10.3).

(e) Build a fully engineered flash volatilizer prototype, with a motorized automatic screw feed, controls etc. to check feasibility for continuous use of this method (Section 9.4 and 10.4).